LLNL-CONF-554371

LAWRENCE LIVERMORE NATIONAL LABORATORY

A Langmuir Probe Diagnostic for Use in Inhomogeneous, Time-Varying Plasmas Produced by High-Energy Laser Ablation

J. R. Patterson, J. A. Emig, K. B. Fournier, P. P. Jenkins, K. M. Trautz, S. W. Seiler, J. F. Davis

May 2, 2012

High-Temperature Plasma Diagnostics
Monterey, CA, United States
May 6, 2012 through May 10, 2012

A Langmuir Probe Diagnostic for Use in Inhomogeneous, Time-Varying Plasmas Produced by High-Energy Laser Ablation[a)]

J. R. Patterson,[1,b)] J. A. Emig,[1] K. B. Fournier[1], P. P. Jenkins[2], K. M. Trautz[2], S. W. Seiler[3], and J. F. Davis[3]

[1]*Lawrence Livermore National Laboratory, Livermore, CA 94551, USA*
[2]*U. S. Naval Research Laboratory, Washington, D. C. 20375, USA*
[3]*Alme and Associates, Alexandria, VA 22307, USA*

(Presented XXXXX; received XXXXX; accepted XXXXX; published online XXXXX)
(Dates appearing here are provided by the Editorial Office)

Langmuir probes (LP) are used extensively to characterize plasma environments produced by radio frequency, pulsed plasma thrusters, and laser ablation. We discuss here the development of a LP diagnostic to examine high-density, high-temperature inhomogeneous plasmas such as those that can be created at the University of Rochester's Laboratory for Laser Energetics OMEGA facility. We have configured our diagnostic to examine the velocity of the plasma expanding from the target. We observe velocities of approximately 16-17 cm/μs, with individual LP currents displaying complex structures, perhaps due to the multiple atomic species and ionization states that exist.

I. INTRODUCTION

Following the pioneering work of Langmuir[1,2] and subsequently Druyvestein[3], measurements of plasma properties, namely plasma density and temperature, via an electrode placed directly into the plasma have proliferated and diversified into the commonplace Langmuir probe (LP) diagnostics of today. Measurements of plasma density and temperature are straightforward for an ideal cylindrical probe (one that does not disturb the plasma) in a stable plasma. In practice, real probes in plasmas with potential and density instabilities require geometries such as the asymmetric double probe and triple probe, which minimize the effects of the former complications (see e.g. Ref. 4 and references therein). Such diagnostics are routinely used in conditions of $n \sim 10^2 - 10^{15}$ cm^{-3}, $T_e \sim 1 - 100$eV corresponding to plasmas generated by glow discharge, RF, pulsed-plasma thrusters and tokomaks. More recently, LP diagnostics have been applied to higher density plasmas $n \sim 10^{19}$-10^{21} cm^{-3} produced by laser ablation.

Solar cells are frequently used as power sources for satellites, and are thus exposed to a radiation-rich environment[5]. Radiation incident on these solar cells has the potential to disrupt commercial satellite networks. To determine whether such a disruption could occur, an appropriate environment must be created in the laboratory. In order to create an appropriate x-ray environment, we generate a high-density $n \sim 10^{22}$ cm^{-3} plasma by laser ablation and use an array of LPs, positioned a few 10s of cm from the source, for characterization. It is important to discriminate between the x-ray effects at the test position and effects from the arrival of plasma generated from the source. To this effect, Langmuir probes can be used to measure the expansion velocity of an inhomogeneous source plasma via the arrival of the leading edge at multiple locations. We report here initial tests of a LP diagnostic composed of an array of single cylindrical probes.

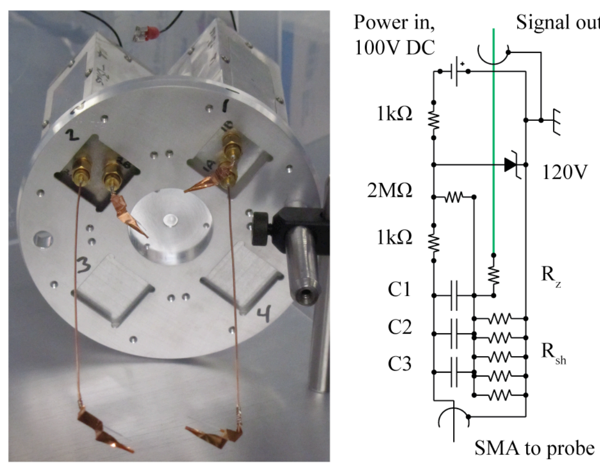

FIG. 1. Photograph of XLPD (left) and schematic of negative bias probe circuit (right). Two pairs of probes and two debris shields occupy the four positions in the modified XRSA cassette. One 2.5cm and one 20cm Cu-foil shielded probe are associated with each bias box seen behind the cassette face.

II. DESIGN & INTEGRATION

The Langmuir probe diagnostic (XLPD) developed for use at the University of Rochester's Laboratory for Laser Energetics OMEGA facility is shown in Fig. 1 (left). Either two or four pairs of cylindrical single probes of differing lengths were combined to measure the velocity of the expanding plasma from the source. Each cylindrical probe consisted of a semi-rigid, 0.86 mm diameter, 50Ω coaxial cable. The exposed end of the cable was stripped of its outer conductor and insulator and bent, with the cylindrical axis perpendicular to the direction of flow, in order to increase the surface area exposed to the moving plasma.

[a)]Contributed paper published as part of the Proceedings of the 19th Topical Conference on High-Temperature Plasma Diagnostics, Monterey, California, May, 2012.
[b)]Author to whom correspondence should be addressed: patterson31@llnl.gov.

A thin Cu-foil shield was attached to the outer conductor to prevent direct x-ray loading of the probes and arcing to ground.

Each pair of probes was connected by an SMA-type connector to a custom “bias box” that supplied both the power for biasing the probes and the signal-collection circuitry. A single voltage can be applied to each pair of probes. Fig. 1 (right) shows a schematic for the negative bias probe circuit. The principal components include a shunt resistor array (R_{sh}) across which the signal current is measured, with typical values of 0.1Ω – 11Ω for the resistor array, and an array of discharge capacitors (labeled C1, C2, and C3) to handle charge balance and facilitate measurement of high-frequency signals. The values of the capacitors were chosen to minimize the inductance of the circuit. Depending on the sign of the applied voltage, the electron or ion current can be measured in this way. Two 1kΩ resistors are included as current limiters as well as an additional resistor (R_z) to match the impedance of the 50Ω oscilloscope input. We initially considered that high bias voltages (~100V) might be required for normal operation, therefore a 2MΩ bleed resistor and a 120V Zener diode were incorporated into the circuitry for personnel safety during installation and removal of the diagnostic. It is interesting to note that from our initial testing, ±20V appears sufficient to draw saturation currents for plasmas generated at the OMEGA laser facility.

A modified XRSA cassette[6] served as the basis for our XLPD. This allowed the use of existing railing systems as shown in Fig. 2, therefore simplifying the implementation of this diagnostic in a ten-inch manipulator (TIM). In addition, only minor modification to existing XRSA installation and alignment procedures were needed. Data and power cables are routed out of the TIM, through the target bay, and to a data acquisition area directly beneath the main target bay. Power is supplied to each bias box a by Stanford Research Systems PS350 DC power supply, and the signals are recorded on Tektronix DPO 4054 oscilloscopes, which were triggered via the OMEGA control system master trigger.

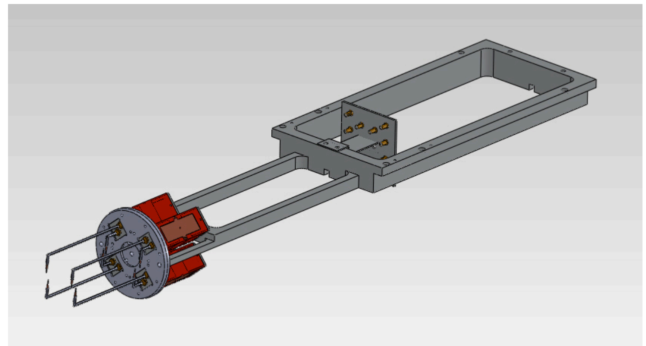

FIG. 2. Model of Langmuir probe diagnostic (XLPD) shown mounted on XRSA rails for TIM installation and alignment. Visible in the model are the bias boxes and a bulkhead with eight SMA feedthrus for signal-cable management.

III. CONFIGURATION & TESTING

Initial experiments were performed at OMEGA on September 14, 2011 and February 29, 2012. In each case 40 beams supplied approximately 20kJ of 0.351µm laser light to the target in a 1ns square pulse. The beams were configured into two sets of 20 beams incident on opposing faces along the target’s cylindrical axis, resulting in peak intensities of the order of 10^{14} – 10^{15} W/cm^2.

Three types of targets were ablated to generate x-rays and plasma for testing the XLPD. Target types comprised stainless-steel-304 (SS) cavities and Fe and Ge aerogel targets. The SS cavities were 3µm thick foils coated on the interior surface of epoxy cylinders 2.0mm ID, 2.0 – 2.2mm in length, and 50µm thick[7]. Aerogel targets were fabricated in cylindrical polyimide tubes of similar dimension to the epoxy cylinders. Ge aerogels[8,9] were ~20% Ge by atom number in SiO_2 and had a density of 3.6mg/cm^3. Fe aerogels[7,10] had the composition $FeO_2HCl_{0.38}$ and had densities ranging from 3 to 16mg/cm^3. It is worth noting that the total mass ablated is largely C, H, and O from either the epoxy or polyimide cylinders.

The XLPD was configured to measure the arrival time of the expanding source plasma at multiple distances from the target, i.e. the expansion velocity. In the first series of 9 shots, two slots of the cassette were populated with pairs of probes (Fig. 1, left), while debris shield were used in the remaining two. Velocity measurements were made between a short probe of 2.5cm and a long probe of either 15 or 20cm. For each shot one probe pair was biased for electron current and the other for ion current, typically ±20V. Cu-foil shields were employed on 6 shots. The cassette face was positioned 35cm from the SS-cavity targets (3 shots), and between 40 and 60cm from the Fe-aerogel targets (6 shots). For the second series of 6 shots, the cassette was fully populated with four Langmuir probe pairs. The probe lengths were 2.5 and 20cm for the short and long probes respectively, and all probes were shielded with Cu-foil. Two pairs were biased similarly to the previous shot series at ±20V while the others were either 0 or 2V. Measurements were made at 35 and 52cm distance from the cassette face for both SS-cavity and Ge-aerogel targets (3 shots each).

For the first campaign, we alternated a pair of cassettes since we did not know what the extent of damage to the probes or shields would be, and we could refurbish them between shots. Based on our observations during that experiment series, we used a single cassette that was loaded into the TIM the previous night and remained there for all 6 shots during the second campaign. Upon recovery we observed that the Cu-foil shields had deflected away from the probe tips during the course of the day, and indeed that data from later in the day look more similar to the unshielded data from the first series. During both experiments, the XLPD was loaded into a TIM with line-of-sight orthogonal to the cylinder axis, i.e. a view of the epoxy or polyimide wall.

IV. RESULTS & DISCUSSIONS

At the ion saturation limit, we observe complex signals representative of the nature of the experiments fielded at OMEGA. In Fig. 3, we see a general broadening and decrease in amplitude of multiple groups of peaks as would be expected for an expanding (slowing and cooling) plasma composed of multiple elemental species and ionization states. Since our targets consisted of metal (or metal-oxide aerogels) contained in plastic or epoxy, we have at least Fe (or Ge), Si, O, C, and H in the source plasma. Also, given the approximately 40kJ of laser drive energy employed, it is quite likely that there are multiple ionization states in this plasma and that a significant amount of recombination occurs later in time. The upper curves show a time-difference in the leading plasma edge of 0.7-0.8µs corresponding to a velocity of ~17cm/µs, while the lower data give an approximate velocity of ~16cm/µs. Both of these numbers, derived from the difference between the measured leading edges of the plasma at different probe distances, are consistent with the velocity derived from the distance between the source and individual probes. We cannot distinguish a

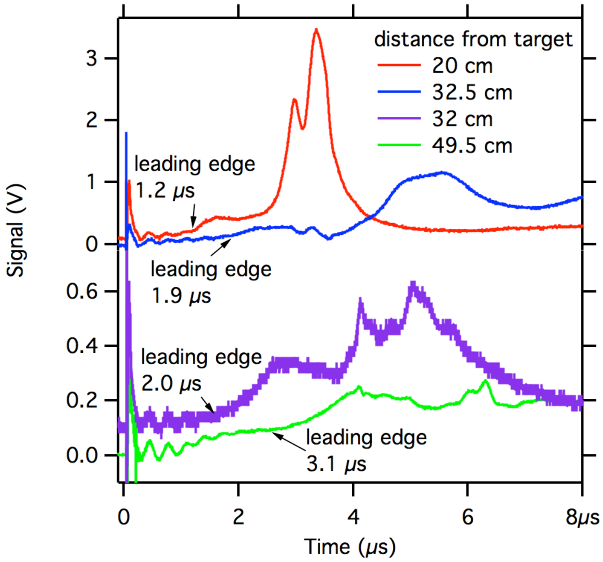

FIG. 3. XLPD data recorded for SS-cavity target shots. All probes are biased at -20V. The upper and lower plots show the arrival of the leading edge for a 15cm probe (darker) and a 2.5cm probe (lighter), and a 20cm (darker) and 2.5cm (lighter) probe respectively.

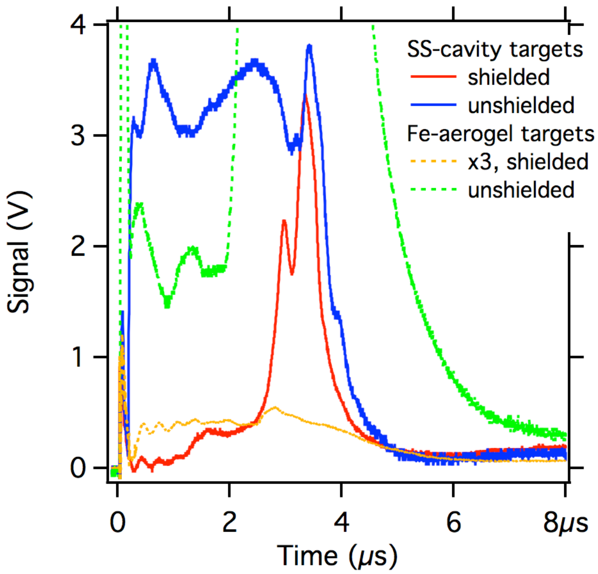

FIG. 4. Comparison of shielded vs. unshielded probe traces for shots on Sept. 14, 2011. For the SS-cavity shots, the probes were 20cm from the target and biased at -20V. The shielded and unshielded probes for the Fe-aerogel shots were 25 and 30cm from the target and -20 and -25V bias respectively.

change in plasma velocity within the ±2cm/μs estimated error in fitting. This relative fitting error may provide some idea of the accuracy of these measurements, but may also be due to variations in the experimental configuration, such as whether or not we exchanged the cassette following each shot. Fig. 4 shows the difference in signal obtained from shielded and unshielded probes for steel cavity and Fe-aerogel targets. It is apparent that the unshielded probes show different structure and increased signal intensity in the first 2 μs, and that these signals are not as prominent after the plasma has propagated an additional 12.5-17.5 cm. In the same time, the shielded probes display relatively weak periodic oscillations. One possible explanation is that time-dependent recombination effects could also be occurring in the plasma, while another is that the initial x-ray burst ionizes a probe's inner conductor and insulator allowing an arc to form between conductors in the coaxial cable used for the probes. The oscillations in the shielded probe signals could be indicative of an interaction between the x-ray induced plasma and the shields themselves. Noting that the 32.5 and 32 cm distances in Fig. 3 were recorded during the September and February campaigns respectively, similar peak structures are observed. We are encouraged by this reproducibility, as it is a good indication that such experiments may be performed over multiple campaigns with consistent targets.

V. SUMMARY

We have successfully developed a Langmuir probe diagnostic for use in time-dependent, inhomogeneous plasma environments created by high-energy laser ablation. We have used our LP diagnostic to measure the arrival of the source plasma at the probes as a function of distance and time, ~16-17cm/μs for our experiments. The stainless-steel cavity targets yield reproducible signals between individual targets shot on the same and different days. Shielding the probes themselves does reduce the intensity of early-time signals, which could be eliminating arcing to ground and/or causing interference and obscuring some portion of the signal.

Since the signals we observe are quite complex, we plan to simplify the targets for our next campaign. By shooting single element foils, we plan to reduce both the number of species and ionization states in the source plasma thereby allowing more identifiable signals. In addition, the incorporation of a new probe geometry would allow us to mitigate the effects of potential variation and possibly remove the need for complex biasing schemes. These modifications will let us attempt to make quantitative measurements of the time-dependence of the source plasma density and temperature. This work was done under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and Defense Threat Reduction Agency IACRO no. 11-45511 "Research Program for X-Ray Experimentation Capability Using Laser Plasma Radiation Sources".

VI. REFERENCES

[1]I. Langmuir and H. M. Mott-Smith, G. E. Rev. **27**, 449, 538, 616, 762, 810 (1924).

[2]H. M. Mott-Smith and I. Langmuir, Phys. Rev. **28**, 727 (1926)

[3]M. J. Druyvesteyn, Z. Phys. **64**, 781 (1930)

[4]E. V. Shun'ko, *Langmuir Probe in Theory and Practice* (Universal Publishers, Boca Raton, 2009).

[5]P. P. Jenkins *et al.*, (in preparation for J. Rad. Effects Research and Engineering).

[6]K. B. Fournier, V. Rekow, J. Emig, J. H. Fisher, C. D. Newlander, R. Horton, and J. Davis, Rev. Sci. Instruments (this conference).

[7]F. Perez *et al.*, (in preparation for Phys. Plasmas).

[8]K. B. Fournier *et al.*, Phys. Plasmas **16**, 052703 (2009).

[9]B. J. Clapsaddle, D. W. Sprehn, A. E. Gash, J. H. Satcher Jr., and R. L. Simpson, J. Non-Cryst. Solids **350**, 173 (2004).

[10]A. E. Gash, J. H. Satcher, and R. L. Simpson, Chem. Mater. **15**, 3268 (2003).